

Modeling amino acid requirements of poultry¹

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Primary Audience: Nutritionists

SUMMARY

Poultry nutritionists should constantly evaluate their feeds and feeding programs in view of the changes that continue to be made to the potential growth rate of broilers and egg production in laying hens with the objective of providing the birds with the optimum economic level of nutrients at all times. In this review, the models generated at Universidade Estadual Paulista (UNESP) Jaboticabal, to estimate the optimum intake of amino acids (AA) for broilers and laying hens are presented. These models were used to estimate the variation in AA intake within a broiler population making use of coefficients of variation that represent the real situation in a commercial broiler operation. The range of AA intakes obtained was compared to some commonly applied feeding programs and recommendations. Based on results of our developed models and other feeding programs, feeds were formulated and growth was predicted using a growth simulation model (Avinesp). The prediction of growth showed that these models are reliable and useful tools to assist the nutritionists in decision making. In a study with laying hens, the Reading model (RM) was used to establish optimum economic AA intakes in a flock of hens. The input variables were the means and standard deviations of egg output and BW, and the relationship between the marginal cost of the AA and the marginal revenue for eggs. Based on this model, the optimum intake of each AA can vary with each of the variables considered. The models proposed in our study enable important decisions to be made regarding AA intakes to be used to obtain optimum economic performance from a population of broilers and laying hens.

Key words: amino acids, broiler, economic, efficiency, laying hens, stochastic model

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DESCRIPTION OF THE PROBLEM

Because of the constant genetic evolution in both broiler chicken and laying hen produc-

tions, nutritionists must constantly adapt their nutritional recommendations and feeding programs to maximize the economical outputs at all times. These management and nutritional decisions must take into account: the animal (growth or egg production potential), environmental conditions, and feed composition, which all affect feed intake (FI) and, consequently, bird performance and economic returns.

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Table 1. Lysine (Lys_m), methionine+cystine (Met+Cys_m), threonine (Thr_m), and valine (Val_m) requirements for maintenance, expressed in different units, obtained in Universidade Estadual Paulista (UNESP) studies¹.

Amino acids (AA)	BW _m	BP _m	AA _m (mg/unit per day)			
	(kg)	(kg)	Bird	BW _{kg}	BW _{kg} ^{0.75}	BP _{kg} ^{0.73} × u
Lys _m	3.81	0.754	123.0	32.3	45.1	151.2
Met+Cys _m	3.78	0.723	59.5	18.9	25.5	87.2
Thr _m	3.95	0.760	44.9	17.1	21.9	75.5
Val _m	4.23	0.854	195.0	46.1	65.4	219.0

BW_m = BW at maturity; BP_m = Body protein weight at maturity of different strains used in trials for each AA; u = BP/BP_m = 1.

¹[51–53].

Dynamic factorial models are used by nutritionists to estimate the nutritional requirements of the average individual of a population of birds, depending on its production rate (i.e., growth or egg production). However, these models are deterministic and do not take into account the inter-individual performance differences of the birds within the population. Considering the genetic potential variability within a population may be taken into account in factorial models, and therefore enable to calculate the differences in the nutrient requirements of the birds within a population.

Mechanistic simulation models represent a promising tool for nutritionists to maximize performance and profitability in production by considering simultaneously genetic, environmental and nutritional factors to establish nutrient requirements and predict FI and performance under different conditions.

In this review, the models developed at the Universidade Estadual Paulista (UNESP) Jaboticabal, Brazil to estimate amino acid (AA) intake for broilers and laying hens are described. Some simulations are presented to demonstrate the usefulness of these models in helping the nutritionists to develop optimal feeding programs.

FACTORIAL MODELS TO ESTIMATE AA REQUIREMENTS

AA Requirement for Maintenance

The maintenance requirements for Lys (**Lys_m**), Met+Cys (**Met+Cys_m**), Thr (**Thr_m**), and Val (**Val_m**) were assessed in metabolism trials based on the nitrogen balance (NB) technique

using adult roosters. These were obtained by linear regression of NB on digestible AA intake. The maintenance requirement was defined as the digestible AA intake needed to maintain the NB equal to zero.

The AA requirements for maintenance were based on body protein weight (**BP**) since there is no AA requirement for the maintenance of lipid reserves [1], which may vary considerably even among individuals with similar BWs [2]. The AA requirements for maintenance were based on BP [1]. The requirements were expressed relative to the mature BP (**BP_m**) and the degree of maturity ($u = BP_t/BP_m$) of the bird, which accounts for the amount of AA required for growth as a proportion of the BP. Expressing AA requirements for maintenance using this approach overrides differences in protein and lipid composition and BW. The coefficients obtained in the UNESP studies are shown in Table 1.

Efficiency of AA Utilization for Growth

Dose-response trials were conducted at UNESP with broilers in which increasing levels of Lys, Val, Met+Cys, and Thr were provided and with body protein deposition using the comparative slaughter technique being measured. The AA deposition (**AAD**) in the body and feathers was assessed based on AA content of feather-free body and feathers.

The efficiency of utilization of dietary AA for growth was considered as the slope of the linear regression of AA deposition as a function of the digestible AA intake for growth. The efficiency of utilization for Lys (k_{Lys}) was 77% (± 1.7), Met+Cys ($k_{Met+cys}$) 78% (± 1.3), Thr (k_{Thr}) 73% (± 0.68), and Val (k_{Val}) 73% (± 0.52).

Table 2. Amino acid (AA) deposition rate (mg/day) in relation to BW gain (g/day)¹.

AA	a	b
Lysine	-23.14 (± 1.206)	13.39 (± 0.725)
Methionine+cystine	-8.45 (± 0.705)	4.58 (± 0.072)
Threonine	-11.15 (± 1.601)	9.13 (± 0.468)
Valine	-22.03 (± 2.873)	9.54 (± 0.526)

¹AAD = $a + b \times \text{BWG}$; where AAD is the amino acid deposition, a is the intercept at y-axis, and b is the coefficient of regression that represents AA requirements for unit of BW gain (BWG).

In addition, depositions of Lys (**DLys**), Met+Cys (**DMet+Cys**), Thr (**DThr**), and Val (**Dval**) were regressed against BW gain (**BWG**) to estimate the deposition of these AA (milligrams/day) or AA requirement for growth, using BWG (grams/day) as the input variable. The coefficients of linear regression are presented in Table 2.

MODELS TO ESTIMATE AA REQUIREMENTS OF BROILERS

Two models were developed to estimate AA requirements of broilers. The first accounts for the maintenance requirement using metabolic BW ($\text{BW}^{0.75}$), and for growth the AA deposition and efficiency of utilization was considered. The M1 model is as follows:

$$\text{AAI} = (\text{AA}_m \times \text{BW}^{0.75}) + [\text{AAD}/k] \quad (\text{M1})$$

AAI is the digestible AA intake (milligrams/day); AA_m is the AA requirement for maintenance (Table 1); $\text{BW}^{0.75}$ is the metabolic BW of the bird (kilograms); and AAD is the AA deposition in the body (milligrams/day) described by the linear function (Table 2): $\text{AAD} = a + b \times \text{BWG}$, where a is the intercept on the y-axis and b is the coefficient of regression that represents AA requirements for unit of BWG. In M1, k is the efficiency of digestible AA utilization for growth. According to this model, the following equations (M1) may be used to calculate the requirement for each AA, expressed in grams digestible AA/bird, per day:

$$\begin{aligned} \text{Lys} &= (45.1 \times \text{BW}^{0.75}) \\ &+ [(-23.14 + 13.39 \times \text{BWG})/0.77] \end{aligned}$$

$$\begin{aligned} \text{Met} + \text{Cys} &= (25.5 \times \text{BW}^{0.75}) \\ &+ [(-8.45 + 4.58 \times \text{BWG})/0.78] \end{aligned}$$

$$\begin{aligned} \text{Thr} &= (21.9 \times \text{BW}^{0.75}) \\ &+ [(-11.15 + 9.13 \times \text{BWG})/0.73] \end{aligned}$$

$$\begin{aligned} \text{Val} &= (65.4 \times \text{BW}^{0.75}) \\ &+ [(-22.03 + 9.54 \times \text{BWG})/0.73] \end{aligned}$$

A more elaborate factorial model is based on the growth model proposed by [3], with maintenance and growth being separated into feather-free body and feathers, assuming that the AA composition differs markedly between the 2 protein pools [4]. The total AA intake was calculated by summing the AA requirements for maintenance and growth, as described by the following equation (M2):

$$\begin{aligned} \text{AAI} &= [(\text{AA}_m \times \text{BP}_m^{0.73} \times u) \\ &+ (\text{FL} \times \text{FP} \times \text{AA}_f) + [(\text{AA}_b \\ &\times \text{BPD} + \text{AA}_f \times \text{FPD})/k] \quad (\text{M2}) \end{aligned}$$

In our studies, the parameters of this model were determined, where AAI is the digestible AA intake (milligrams/bird per day); AA_m is the AA maintenance requirement expressed as BP (mg/ $\text{BP}_m^{0.73} \times u$) presented in Table 1; BP_m refers to that at maturity (kilograms) in Table 3; u is the degree of maturity of the bird ($u = \text{BP}/\text{BP}_m$); and feather loss (**FL**) is equivalent to 0.01 g/g feathers per day [4]. The maintenance requirement for feather protein is proportional to the loss of feathers. Feather protein weight (**FP**; in grams) refers to that presented in Table 3. The AA content in the BP free of feathers (AA_b , milligrams/gram) and feathers (AA_f , milligrams per gram) were 75 and 18 mg/g for Lys, 36 and 76 mg/g for Met+Cys, 42 and 44 mg/g for Thr, and 44 and 60 mg/g for Val [5, 6]. The rate of protein deposition in the feather-free body (**BPD**) is in units of grams/day and the rate of deposition in feathers (**FPD**; grams/day) is calculated as the first derivative of the Gompertz equation [7] using the parameter values from Table 3. In M2, the parameter k expresses the efficiency of AA utilization for deposition in feather-free body and in feathers, and is set at $k_{\text{Lys}} = 0.77$, $k_{\text{Met+cys}} = 0.78$, k_{Thr} and $k_{\text{Val}} = 0.73$. Thus, the M2 equations to

Table 3. The mean and the respective CV and SD used for *Wi*, *Wm*, and *B* to generate a random population of 5,000 broilers of Ross308 strain.

Parameters ¹		BW	Body protein (BP)	Feather protein (FP)
<i>Wi</i>	Mean, kg	0.043	0.004	0.0015
	CV, %	5.0	5.0	5.0
	SD, kg	0.002215	0.0002	0.000075
<i>Wm</i>	Mean, kg	6.544	1.3	0.353
	CV, %	7.0	7.0	7.0
	SD, kg	0.45808	0.091	0.02471
<i>B</i>	Mean	0.039	0.041	0.045
	CV, %	5.5	5.5	5.5
	SD	0.002145	0.002255	0.002475

¹*Wi* is initial weight, *Wm* is the weight at maturity, and *B* is the maturation rate.

calculate the requirement for each AA expressed in milligrams/bird per day are described as follows:

$$\begin{aligned} \text{Lys} = & [(151.2 \times \text{BP}_m^{0.73} \times u) \\ & + (0.01 \times \text{FP} \times 18) \\ & + [(75 \times \text{BPD} + 18 \times \text{FPD})/0.77] \end{aligned}$$

$$\begin{aligned} \text{Met} + \text{Cys} = & [(87.2 \times \text{BP}_m^{0.73} \times u) \\ & + (0.01 \times \text{FP} \times 76) \\ & + [(36 \times \text{BPD} + 76 \times \text{FPD})/0.78] \end{aligned}$$

$$\begin{aligned} \text{Thr} = & [(75.5 \times \text{BP}_m^{0.73} \times u) + (0.01 \times \text{FP} \times 44) \\ & + [(42 \times \text{BPD} + 44 \times \text{FPD})/0.73] \end{aligned}$$

$$\begin{aligned} \text{Val} = & [(219 \times \text{BP}_m^{0.73} \times u) + (0.01 \times \text{FP} \times 60) \\ & + [(44 \times \text{BPD} + 60 \times \text{FPD})/0.73] \end{aligned}$$

Generating a Population of Birds

To determine the AA requirements of a population of birds, a stochastic approach was used following the principles of [5] and [8]. These authors suggested that a population of animals can be generated from random, uncorrelated, and normally distributed values.

The Gompertz parameters *Wi*, *Wm*, and *B* were assumed to be the parameters that can adequately define the variability in the AA requirements of a population of birds. The parameter values from Ross308 genotype (Table 3) were taken as an example to evaluate the ability of

the model in estimating the variability in the AA requirements within a population of birds.

It was considered that the covariance between *Wm* and *B* [9] was $B^* = B \times Wm^{0.27}$ where *B** is the scaled value of *B*. The negative correlation between *B* and *Wm* [10] may be overcome using the scaled rate parameter, $B^* = B \times Wm^{0.27}$ that is uncorrelated with *Wm* [11, 5]. The CV of the *B* and *Wm* values were assumed to vary between 0.06 and 0.10, whereas that of *B** was assumed to be lower, with a CV varying between 0.02 and 0.04 [5]. The CV of the the lipid:protein ratio (**LPR**) in the body at maturity (i.e., *LPRm*) was supposed to be 0.04 [1].

To generate a population of birds, random values were generated from *Wi*, *Wm*, and *B* to produce 5,000 individuals. The growth rate was simulated by setting the CV at 5.0% for *Wi*, 5.5% for *B*, and 7.0% for *Wm*. The same CV was used for BW, BP and FP. The mean (μ) and SD (σ) for *Wi*, *Wm*, and *B* are presented in Table 3.

Based on the generated random values of *Wi*, *Wm*, and *B*, it was possible to estimate the *Wt* variable for BW, FW, BP, and FP as described by [3]:

$$\begin{aligned} Wt = & Wm \times \exp[-\exp((\ln(-\ln(Wi/Wm))) \\ & - (B \times t))], \end{aligned}$$

where *Wt* is the weight (kilograms) estimated for age *t* (days); *Wm* is the weight (kilograms) at maturity; *Wi* is the weight (kilograms) at hatching; and *B* is the rate of maturing (per day).

In Table 4 are the mean and SD of 5,000 simulated individuals at weekly intervals from 1 to 49 d age.

Table 4. Estimation of BW, weight gain (BWG), the protein weight of feather-free carcass (BP) and feathers (FP), rate of protein deposition in the feather-free carcass (BPD) and feathers (DFP), and corresponding SD of 5,000 male Ross308 broilers.

Age (day)	BW (g)	BWG (g/day)	BP (g)	BPD (g/day)	FP (g)	FPD (g/day)
1	52 ± 3	10 ± 1	5 ± 0.2	1 ± 0.1	2 ± 0.5	0 ± 0.0
7	141 ± 10	21 ± 2	17 ± 1.3	3 ± 0.3	7 ± 1	1 ± 0.1
14	351 ± 32	40 ± 5	50 ± 5	7 ± 0.8	20 ± 2	3 ± 0.3
21	702 ± 72	60 ± 7	113 ± 13	11 ± 1.4	44 ± 5	4 ± 0.5
28	1,190 ± 124	78 ± 8	207 ± 24	16 ± 1.7	78 ± 9	5 ± 0.6
35	1,780 ± 178	89 ± 8	327 ± 36	18 ± 1.6	117 ± 13	6 ± 0.6
42	2,419 ± 227	92±7	461 ± 45	19 ± 1.2	158±16	6 ± 0.7
49	3,059 ± 266	89 ± 6	596 ± 52	19 ± 0.8	197 ± 20	5 ± 0.7

Table 5. Estimation of lysine, methionine+cystine, threonine, and valine required intakes calculated by 2 factorial models using a simulated population of 5,000 individuals Ross308 strain¹.

Age	Lysine			Met+Cys			Threonine			Valine		
	μ-σ	μ	μ+σ	μ-σ	μ	μ+σ	μ-σ	μ	μ+σ	μ-σ	μ	μ+σ
Model 1												
1	117	126	134	94	99	105	89	95	100	102	108	114
7	277	306	336	228	246	265	214	233	252	245	266	286
14	568	637	706	473	517	561	444	488	532	509	558	607
21	921	1,029	1,137	772	841	910	724	793	863	831	908	985
28	1,252	1,379	1,506	1,048	1,131	1,214	985	1,068	1,151	1,132	1,225	1,318
35	1,486	1,607	1,727	1,238	1,323	1,408	1,170	1,252	1,333	1,347	1,439	1,531
42	1,592	1,688	1,785	1,318	1,399	1,480	1,255	1,326	1,397	1,446	1,529	1,611
49	1,573	1,645	1,717	1,298	1,376	1,454	1,246	1,306	1,367	1,438	1,512	1,586
Model 2												
1	115	124	132	94	100	105	89	94	100	101	107	113
7	294	327	360	241	262	282	227	248	269	259	283	306
14	642	727	812	524	575	627	495	549	602	565	624	683
21	1,089	1,228	1,368	876	960	1,044	835	923	1,011	952	1,049	1,146
28	1,526	1,694	1,862	1,207	1,310	1,412	1,161	1,269	1,377	1,323	1,441	1,560
35	1,849	2,009	2,170	1,438	1,542	1,646	1,399	1,504	1,610	1,592	1,710	1,827
42	2,008	2,133	2,259	1,536	1,632	1,728	1,513	1,602	1,691	1,721	1,823	1,926
49	2,003	2,088	2,173	1,513	1,601	1,689	1,509	1,579	1,649	1,717	1,802	1,888

¹Model 1: AAI (mg/day) = (AA_m × BW^{0.75}) + (D/k). Model 2: AAI (mg/day) = [(AA_m × BP_m^{0.73} × u) + (FL × FP × AA_f)] + [(AA_b × BPD + AA_f × FPD)/k]. μ = mean; σ = SD.

Applicability of Models to Estimate AA Requirements

The growth simulation of the 5,000 individuals made it possible to demonstrate how variation in weight and growth rate affected AA intake. The M1 and M2 models were used to estimate Lys, Met+Cys, Thr, and Val intakes required to sustain maintenance and growth. AA intake required by each individual for maintenance and growth are calculated using BW, BP, BWG, BPD and FPD in a factorial model. In these models, the maintenance is adjusted according to BW or protein weight of the bird; therefore, the rate of maturing (*B*) is the

main parameter that defines variation between individuals in the population. The M1 model estimated lower required intakes of all four AAs compared with the M2 model (Table 5). The fact that the *B* value used for gain in BW (0.039) is smaller than for BP (0.041) resulted in lower requirements. The difference between the models is the estimate of the rate of AA deposition in the body. M1 considers a linear relationship between the deposition of AA and BWG, whereas model M2 considers each AA as a fixed proportion of the protein deposited in carcass or feathers. Differences between the models are explained by their input variables. Based on the results of

this simulation, BW and BWG (inputs in M1 model) were not adequate to estimate the AA requirements. On the other hand, the M2 model, which considered the BP, FP, BPD, and FPD, predicted intake values which are consistent with recent reports [12–14].

In order to compare our results with those recommended in the literature, the daily intakes of Lys, Met+Cys, Thr, and Val estimated by model M2 are expressed as a percentage of diet using the suggested daily FI according to Ross308 guidelines [15]. The dietary contents of Lys, Met+Cys, Thr, and Val required to meet the potential growth of broilers (% of diet) were also calculated according to the feeding programs suggested by the National Research Council (NRC) [16], Ross308 guidelines [15], and Brazilian Tables for Poultry and Swine (BTPS) [17], and these are presented and compared in Table 6.

The first application of the model is flexible to set the concentration of AA in the diet. Model 2 estimated the average required Lys concentration for birds between 1 and 21 d age as 1.24% of the diet, and for birds between 22 to 42 d age as 1.00%. Table 6 also reports the calculated requirements for the lower 16% of birds ($\mu-\sigma$) and for the upper 84% of birds ($\mu+\sigma$). For Lys, the corresponding values are 0.912 and 1.089% between 22 and 42 d age. A brief literature review shows recommendations generally within the range recommended by model ([18]: Lys = 1.060%; [19]: Lys = 1.000%; [20]: Lys = from 0.872 to 1.055%; [21]: Lys = 1.090%; [13]: Lys = 1.040%; [14]: Lys = 1.005%).

Ross308 feeding program guidelines [15] are also reported in Table 6. Compared to these guidelines, the average Lys recommendations from our model were +15.7, +7.7, and +4.7% greater than these guidelines, for birds between the age of 0 to 10, 11 to 24, and 25 to 42 d, respectively. When compared to the Lys recommendations of the BTPS [17], the average requirements calculated from our model were 8.2% greater between 0 and 7 d, 5.9% less between 8 and 21 d, 7.6% less between 22 and 33 d, and 11.2% less between 34 and 42 d age. In general, the model estimated greater average Lys requirements in the initial phase compared to NRC [16], Ross308 guidelines [15] and the BTPS [17]. However, our estimate of average Lys requirements during this

Table 6. Recommendations for lysine, methionine+cystine, threonine, and valine (% of diet) for broiler chickens according to our developed model and different feeding programs of National Research Council (NRC), Ross308 guidelines, and Brazilian Tables for Poultry and Swine (BTPS)¹.

Source	Phase	Lysine			Methionine + cystine			Threonine			Valine		
		Level	$\mu-\sigma$	μ	$\mu+\sigma$	Level	$\mu-\sigma$	μ	$\mu+\sigma$	Level	$\mu-\sigma$	μ	$\mu+\sigma$
NRC [16]	1 to 21	1.100	1.114	1.243	1.372	0.900	0.911	0.989	1.068	0.800	0.859	0.941	1.023
	22 to 42	1.000	0.912	1.000	1.089	0.720	0.715	0.771	0.827	0.740	0.692	0.750	0.807
Ross308 guidelines [15]	0 to 10	1.270	1.239	1.365	1.491	0.940	1.017	1.095	1.174	0.830	0.957	1.037	1.117
	11 to 24	1.100	0.997	1.126	1.255	0.840	0.808	0.886	0.964	0.730	0.766	0.848	0.930
	25 to 42	0.970	0.900	0.983	1.066	0.760	0.703	0.756	0.810	0.650	0.682	0.736	0.791
	1 to 7	1.320	1.304	1.428	1.552	0.950	1.071	1.148	1.225	0.820	1.007	1.085	1.164
BTPS [17]	8 to 21	1.220	1.017	1.148	1.279	0.880	0.828	0.907	0.987	0.790	0.783	0.866	0.949
	22 to 33	1.130	0.940	1.044	1.149	0.830	0.744	0.808	0.872	0.740	0.716	0.783	0.850
	34 to 42	1.060	0.875	0.941	1.008	0.770	0.675	0.721	0.767	0.690	0.660	0.705	0.750

¹The daily intakes of amino acids estimated by model M2 are expressed as a percentage of diet using the daily feed intake according to Ross308 guidelines [15].

initial phase lies within the range (from 1.35 to 1.38% diet) determined by [22]. In another study, [23] found the best FCR in diets when Lys was between 1.3 and 1.4%.

In general, the model estimated greater average requirements for Met+Cys than NRC [16], Ross308 guidelines, [15] and BTPS [17]. However, the average Met+Cys requirements derived from the model were close to those of [24] and [25] who found the best FCR from 0.964 to 1.034% Met+Cys in the diet of broilers in the initial phase (1 to 16-days-old). From 22 to 42 d, the recommendations found in the literature ([26]: Met+Cys = 0.896%; [27]: Met+Cys total = 0.880%; [28]: Met+Cys = 0.793%; [29]: Met+Cys = 0.661%; [24]: Met+Cys = 0.661%) were within the range of 0.675 to 0.872% recommended by our developed model.

The NRC [16] estimate of Thr requirements during the first 21 d (0.8% diet) is lower than the range predicted by our model (0.859 to 1.023% diet). The Ross308 guideline [15] recommendations of 0.83% diet for 0 to 10 d were lower than the range of 0.96 to 1.12% predicted by our model. Similarly, for 11 to 24 d age, the Ross308 guideline recommendation (0.73% diet) was also lower than the range predicted by our model (0.77 to 0.93%). [30] showed improvements in BWG and FCR of male chicks when fed diets containing 0.72% Thr during the first 21 d age. Similarly, [31] found a Thr requirement of 0.72% for male broilers from 7 to 21 d. These values are lower than the range of 0.78 to 1.16% predicted by the model for this period considering the BTPS [17] feeding program. However, the recommendations of 0.79% by the BTPS [17] is within the range of the values estimated by our model.

For 22 to 42 d age, our predicted Thr requirement (0.75%) was close to the NRC [16] recommendation (0.74%) and higher than the Ross308 guideline [15] recommendation (0.65%) for 25 to 42 d. The Thr recommendations by the model are in agreement with the requirement of 0.78% for male broilers found by [32]. For 34 to 42 d age, our recommendation (0.70%) was close to the BTPS [17] recommendation (0.69%), which is also in accordance with [33] who found a Thr requirement of 0.70% from 30 to 42 d.

In general, the Val recommendations (% diet) predicted by the model were higher than those of NRC [16], Ross308 guidelines [15], and BTPS [17]. It has been reported digestible Val requirements of 0.81% for BWG and 0.82% for FCR in broilers chicks from 1 to 21 d [34]. These values are out of the range estimated by the model in the present study (from 0.98 to 1.16%). However, our recommendations were in agreement with the results of [35]. They conducted a meta-analysis using neural network models and concluded that the optimum Val requirement for BWG and FCR would be 1.09 and 1.104% diet, respectively.

The dietary Val recommendations by BTPS [17] of 0.86% and NRC [16] of 0.82% from 21 to 42 d are in the range of the predicted values from the model in this study (0.75 to 0.96% diet). These values are also in the range of the recommendations of [36] which were 0.82% for BWG and 0.81% for FCR from 21 to 42 d.

Responses of Broilers Fed According to Feeding Programs

The responses of broiler chickens fed according to NRC [16], Ross308 guidelines [15], and BTPS [17] feeding programs (Table 7) were compared to those birds fed based on our models recommendations. The Avinesp model developed at UNESP Jaboticabal was used to simulate the responses.

The theoretical basis of the Avinesp model has been detailed by [37]. The model follows the theory proposed by Emmans and co-workers [38, 4, 39, 9, 5]. The model estimates the desired and actual FI, BW, body composition, and nutrient requirements for broilers and pullets. The model predicts the growth of the birds in response to variation in diet, genotype, and environment.

Simulations of Responses in Broilers

To evaluate the recommendations of Lys, Met+Cys, Thr, and Val presented in Table 6, diets based on maize, soybean meal, and crystalline AA were formulated. The diets were formulated using only the recommendations of the AA (Lys, Met+Cys, Thr, and Val) presented in Table 6 whilst maintaining the requirements of other nutrients (AMEn, vitamins, minerals, and

Table 7. Estimated feed intake (FI, g/day) and BW (g) of broiler chickens from 1 to 42 d at weekly intervals according to 3 feeding programs and compared to simulated results using the Avinesp model.

Age (days)	Feeding program											
	NRC ¹		Model ²		Ross 308 Guideline ³		Model ²		BTPS ⁴		Model ²	
	FI	BW	FI	BW	FI	BW	FI	BW	FI	BW	FI	BW
1	11	61	11	61	11	61	11	61	11	61	11	61
7	19	129	22	140	23	143	25	150	25	148	25	150
14	37	268	48	326	48	331	51	351	53	350	51	343
21	66	513	89	659	84	644	92	692	92	697	91	684
28	104	889	136	1,148	132	1,122	142	1,199	138	1,203	139	1,191
35	155	1,430	177	1,788	181	1,754	183	1,852	187	1,851	190	1,834
42	190	2,113	221	2,517	215	2,480	224	2,588	232	2,600	227	2,578

¹National Research Council, Nutrient Requirements of Poultry [16].
²Model:AAI (mg/day) = [(AA_m × BP_m^{0.73} × u) + (FL × FP × AA_f)] + [(AA_b × BPD + AA_f × FPD)/k].
³Ross308 Guideline [15].
⁴Brazilian Tables for Poultry and Swine [17].

so on) the same across all diets. The diets were entered in the Avinesp model in accordance with the feeding programs recommended by NRC [16], Ross308 guidelines [15] and BTPS [17]. The performance was simulated with the diet as the only source of variation, while genotype and environment remained constant. The responses in FI and BW from 1 to 42 d age are presented in Table 7.

As mentioned previously, calculating the required AA intakes using a factorial model enables the AA requirements to be defined accurately. The FI and BW obtained according to our model were higher than those from NRC [16] and Ross308 guidelines [15].

Over the 42 d simulation, the bird would receive an average dietary Lys concentration of 1.16% using the model and 1.11% with the Ross308 guidelines [15] as the feeding program. Apparently, using levels of 1.27 and 1.10% Lys from 0 to 10 and 11 to 24 d age, respectively, may affect the performance of the birds, resulting in a cumulative effect on the subsequent period, since the recommendations for 25 to 42 d from the model and Ross308 guidelines [15] were similar.

The growth curves of broilers fed according to our model and the 3 feeding programs are shown in Figure 1.

The differences between NRC [16] and the model, and between Ross308 guidelines [15] and the model are shown in Figures 1.A and 1.B. The BW of broilers at 42 d fed according to NRC [16] and for Ross308 guidelines [15] were 403 and 107 g lower than those based on the model,

respectively. Figure 1.C shows that the growth curve predicted by our model and that of BTPS [17] are similar. The BW at 42 d age predicted by BTPS [17] and our model recommendations were 2.600 and 2.578 kg, respectively. But there are differences in the recommended Lys levels of our model compared to the BTPS [17] recommendations. Values from our model were 8% higher for 1 to 7 d, 6% lower for 8 to 21 d, 7.6% lower for 22 to 33 d, and 11% lower for 34 to 42 d, respectively. These differences should be of interest to companies who attempt to reduce feed costs while providing adequate nutritional levels to maximize responses in BW and FCR. The Avinesp model still does not perform an economic analysis, but it provides a useful tool to understand the differences between the recommendations regarding various AA.

The feeding programs investigated here were also evaluated using an economic analysis approach (Table 8). The objective was to show how the results of performance, cost of feed, and revenue change across the 3 feeding programs and our model. However, the outcomes are dependent on genotype and variability of growth parameters, prices of feed ingredients, and broiler price. Therefore, the results would change based on the specifics of a given production situation. These simulations were performed with an educational purpose and to show the validity of the models and their application.

Based on the results obtained by the simulation study (Table 7), feed costs per bird and gross revenues obtained from the sale of poultry produced at 42 d age were calculated. The gross

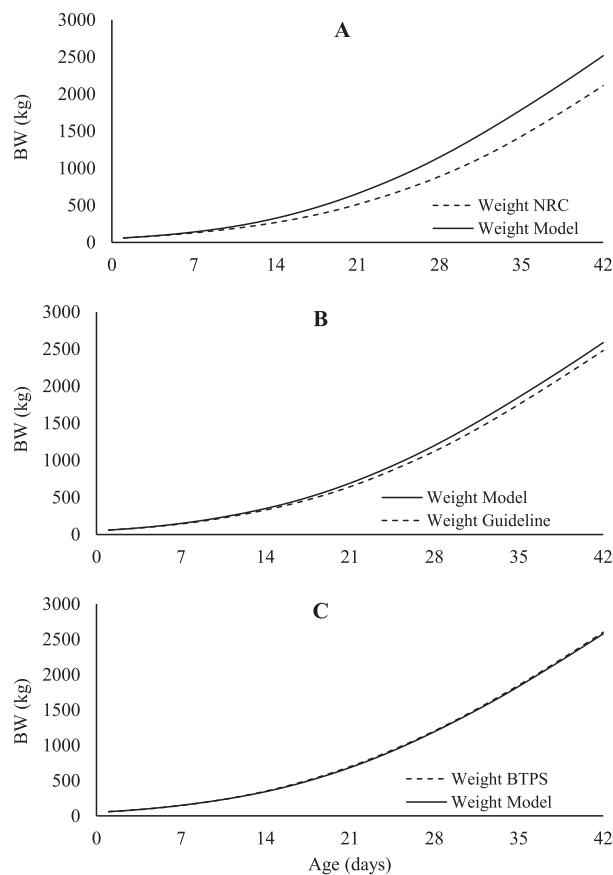


Figure 1. Growth curves simulated by Avinesp, according to amino acid (AA) requirements recommended by National Research Council (NRC) [16] (A), Ross308 guidelines [15] (B), and Brazilian Tables for Poultry and Swine (BTPS) [17] (C) compared to our model.

margin was calculated as the difference between gross revenue and feed cost. The feed cost at 42 days was calculated using a weighted mean for each day of feed utilization.

The feed cost formulated by the model was 0.5% lower, 1.36% higher, and 0.22% higher in relation to the cost of the feed formulated using the NRC [16], Ross308 guideline [15], and BTPS [17], respectively. The combination of higher feed unit costs as well as greater FI resulted in higher feeding costs with the AA levels from our model compared to those of NRC [16], Ross308 guideline [15], and BTPS [17]. The increase in feed costs based on the aforementioned references was 21.92, 6.33, and -0.45%, respectively. On the other hand, the revenue from the sale of the chicken resulted in a greater gross margin of 19.1% for the model when compared to the NRC [16], while, a greater gross margin of

4.3% compared to the Ross308 guideline [15], but a reduced gross margin of -0.85% compared to the BTPS [17].

The reduction in profit margin is attributed to the nutrient levels of the model during 1 to 7 d age. To meet the nutritional levels of Lys, Met+Cys, Thr, and Val during this period required a substantial increase in the inclusion rates of crystalline AA, which resulted in a 3.6% increase in feed cost. This factor affected the profit margin, since the other diets had similar costs.

Application of Simulation Model (Avinesp) to Evaluate the Optimum Economic Level of AA

The idea of how nutritionists can use the Avinesp software as a tool to evaluate the

Table 8. Economic analysis of the different feeding programs for broilers compared to models¹.

Variables	Feeding programs					
	National Research Council (NRC) ²	Model ³	Guideline ⁴	Model ³	Brazilian Tables for Poultry and Swine (BTPS) ⁵	Model ³
Feed intake (kg/bird)	3.442	4.198	4.145	4.348	4.405	4.376
BW (kg/bird)	2.113	2.517	2.480	2.588	2.600	2.578
Diet cost (\$/kg) ⁶	0.459	0.459	0.452	0.459	0.456	0.457
Feed cost (\$/bird) ⁷	1.579	1.925	1.875	1.994	2.011	2.002
Revenue (\$/bird) ⁸	2.301	2.741	2.701	2.818	2.831	2.807
Margin (\$/bird) ⁹	0.722	0.815	0.825	0.824	0.820	0.805

¹Calculated values based on the data presented in Table 7.

²NRC, Nutrient Requirements of Poultry [16].

³Model M2.

⁴Guideline, Ross 308 [15].

⁵BTPS [17].

⁶Diet cost = (diet cost₁ × time₁ + diet cost₂ × time₂ + diet cost₃ × time₃ + diet cost_n × time_n)/42.

Diet cost: NRC: 1 to 21 and 22 to 42 d: 0.469 and 0.449 \$/kg, respectively; Model: 1 to 21 and 22 to 42 d: 0.470 and 0.448 \$/kg, respectively.

Diet cost: Guideline: 1 to 10, 11 to 24 and 25 to 42 d: 0.476, 0.458 and 0.436 \$/kg, respectively; Model: 1 to 10, 11 to 24, and 25 to 42 d: 0.486, 0.462, and 0.442 \$/kg, respectively.

Diet cost: BTPS: 1 to 7, 8 to 21, 22 to 33, and 34 to 42 a: 0.467, 0.456, 0.459, and 0.446 \$/kg, respectively; Model: 1 to 7, 8 to 21, 22 to 33, and 34 to 42 d: 0.484, 0.457, 0.459, and 0.436 \$/kg, respectively.

⁷Feed cost = feed intake × diet cost.

⁸Revenue = kg BW × broiler price (1.09 \$/kg).

⁹Margin = revenue - feeding cost.

optimum economic level of AA in broiler’s diet will be discussed.

A simulation was conducted to predict the response of male broilers (Ross308) to different levels of digestible Lys during 22 to 42 d age under the standard breeding condition. Ten levels of digestible Lys range from 0.845 to 1.295% were studied. Diets were formulated on ideal protein basis with Lys as the first limiting AA. The ideal AA:Lys ratio was increased by 10%. Two maize–soybean meal based diets were formulated, one to reach 0.845% digestible Lys and the other one to have 1.295% Lys. Through dilution technique the other desired levels of Lys were obtained. Within all diets the amino acid ideal ratio, AMEn (3,150 kcal/kg), vitamins, and minerals were kept constant. The birds responses fed each of diet in the period of 22 to 42 d age were simulated (Table 9).

Response functions of FI, BWG, and FCR were fitted to the data of Table 9. Different functional forms were considered, including the monomolecular function [40], but the data suggested that a continuous and smooth 2-segments model of the following form be

Table 9. Responses of Ross308 broilers fed different levels of digestible lysine (Lys; %) from 22 to 42 d age obtained through Avinesp simulation¹.

Lys	Feed intake	BW gain	FCR
0.845	132.6	70.1	1.892
0.895	142.5	78.5	1.816
0.945	149.1	83.8	1.778
0.995	150.7	85.7	1.758
1.045	150.3	85.8	1.750
1.095	149.7	85.7	1.746
1.145	149.4	85.7	1.744
1.195	149.3	85.7	1.743
1.245	149.3	85.7	1.743
1.295	149.2	85.7	1.742

¹Feed intake is in grams/bird per day; and BW gain is in grams/bird per day.

fitted:

$$E[Y|Lys] = \begin{cases} \alpha + \beta Lys + \gamma Lys^2 & \text{if } Lys \leq x_0 \\ \alpha + \beta x_0 + \gamma x_0^2 & \text{otherwise} \end{cases}$$

with the constraint that $x_0 = \frac{-\beta}{2\gamma}$ to impose smoothness (i.e., so that the first derivative of the two segments with respect to Lys need to coincide at x_0). This function did fit the data

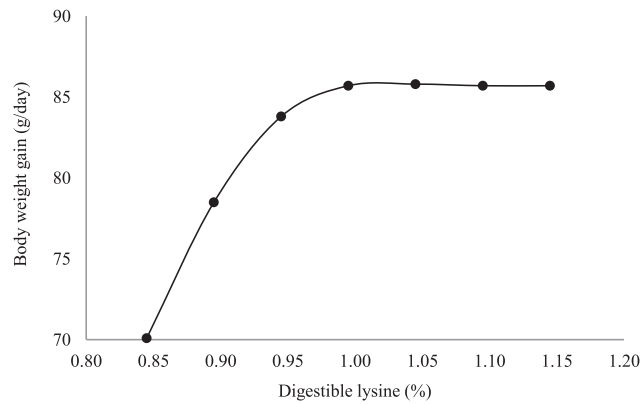


Figure 2. Simulated data points (dots) and smooth, 2-segments response function of BW gain to digestible lysine.

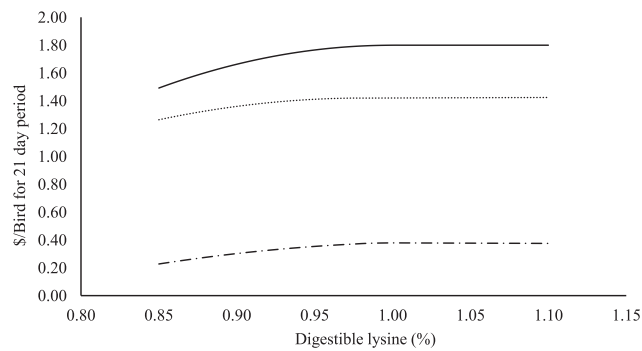


Figure 3. Gross income (dash), feed costs (dot), and gross margins (dash-dot) per bird fed diets of varying digestible concentrations. Prices used are \$0.45/kg for the base feed at 0.85% lysine (Lys), \$1.20/kg Lys, and \$1.00/kg live bird.

extremely well (Figure 2) and was selected to conduct the rest of the analysis.

In addition to providing solid performance results, the level of digestible Lys to be fed should be maximizing profits. Profits are equal to the gross income from the sale of the bird (i.e., BWG $\times$ unit price of live bird), minus feed costs (i.e., FI $\times$ unit price of feeds), minus all other costs (which to a reasonable proxy can all be considered fixed with respect to the Lys level being fed). Therefore, the Lys level that maximizes gross margins (gross revenues minus feed costs) would also be the Lys level that maximizes profits. Prices used for the analysis were \$0.45/kg for the based diet at 0.85% digestible Lys, L-Lys HCl at \$1.20/kg (we assumed that all the Lys above the 0.85% level would be from synthetic L-Lys), and the price of live broilers at

\$1.00/kg. Under this price scenario, the price of the diet is increasing by \$1.20 per metric ton for each 0.1% increase in digestible Lys. Results of this economic analysis are shown in Figure 3.

Given the set of prices used, the optimal level of digestible Lys was found to be 1.00%, resulting in gross margins of 37.95¢ per bird over the 21-day period. This Lys level is also the level that maximizes BWG (i.e., the x_0) in the segmented function. For this simulation, the optimal level of Lys was found to be very inelastic to changes in prices. In fact, the doubling of any of the three prices used affected the optimum Lys level by less than 0.01%. These results are indicative that under the Avinesp model, the optimum dietary Lys is very insensitive to prices and very near the Lys level that maximizes BWG.

Table 10. Average maximum egg output ($E_{\max}$), SD of egg output (σ EO), average body weight, SD of BW (σ W), milligrams AA required per g egg output (a) and per kg BW (b), obtained from research projects at Universidade Estadual Paulista (UNESP)¹.

Amino acids	$E_{\max}$	σ EO	BW	σ BW	a	b
Lysine	59.9	6.04	1.53	0.15	8.58	36.6
Methionine + cystine	63.9	10.0	1.53	0.12	7.96	50.8
Threonine	64.0	10.0	1.53	0.12	6.73	37.2

¹[54]

MODELS TO ESTIMATE AA REQUIREMENTS FOR LAYING HENS

The optimum economic AA intakes for laying hens was determined using the Reading model (RM), taking into account the variation in BW and potential egg output ($E_{\max}$) in the population as well as changes in egg revenue and feed prices. Three dose response trials were conducted at the UNESP, to enable the optimum economic AA intakes of Lys, Met+Cys, and Thr to be calculated. The egg production response was obtained by increasing dietary levels of each AA.

The RM [41] was fitted to the egg output and AAs intake using the EFG Software [42]. The model is described by the following equation:

$$A_{\text{opt}} \left(\frac{\text{mg}}{d} \right) = a \times E_{\max} + b \times \text{BW} + x \sqrt{a^2 \times \sigma^2 E_{\max} + b^2 \times \sigma^2 \text{BW}}$$

where $E_{\max}$ is the maximum egg output, g/day; $\sigma E_{\max}$ is the SD of $E_{\max}$; BW is in kilograms; σ BW is the SD of BW; a is the intake of AA required per gram of egg output, milligrams per gram; and b is the intake of AA required per kilogram of BW, milligrams per kilogram. The optimum intake of the AA (milligrams/bird per day) is that which leaves a proportion $a \times k$ of the individual requirements unsatisfied [41]. The value of x represents the SD; k is the marginal cost of 1 milligram AA (\$/milligram) divided by the marginal revenue of 1 g egg output (\$/gram).

Estimates of the coefficients a and b of the RM are given in Table 10. Fitting the RM to response data such as those measured here has many advantages over other curve-fitting procedures used to interpret response data [43, 44] particularly because the coefficients generated have biological meaning, and the optimum economic intake of the limiting AA may be determined by considering the marginal cost of AA

and the marginal revenue for eggs. This model has been used widely to describe responses of laying hens to limiting AA intake.

The intakes of Lys, Met+Cys, and Thr required per gram egg output (a coefficient) were calculated to be 8.58, 7.96, and 6.73 mg/g, respectively. For Lys, the values are very close to those reported by [45] of 9 mg/g, [46] of 9.5 mg/g, and [47] of 11.03 mg/g. For Met+Cys the value is higher than those of [48] of 4 mg/g, [45] of 4.7 mg/g, and [47] of 3.02 mg/g. For Thr, the value was close to those reported by [49] of 8.7 mg/g. The important factor is that these coefficients have biological meaning, which is apparent when comparing the intake required with the amount of each AA in the egg.

The RM is not the ideal approach for determining the maintenance requirement of AA. It has been argued that the maintenance requirement should be based on BP mass and not BW [2], and that this should be measured independently of egg production [50]. Nevertheless, the b coefficient obtained here for Met+Cys (50.8 mg/kg) is higher than those reported in the literature: [48] reported a value of 25 mg/kg while [45] estimated this to be 31 mg/kg. For Thr, the value of 37.2 mg/kg is close to that reported by [49] of 43.5 mg/kg. The Lys maintenance requirement obtained in this study (36.6 mg/kg) was considerably less than that reported by [46] of 90 mg/kg, but nearly the same as that reported by [47] of 37.0 mg/kg and close to [51] of 32.3 mg/kg. The coefficients measured by [52] using a direct method of measurement differed from those reported here for Met+Cys (19 mg/kg) and for Thr (17 mg/kg). Clearly, more research is needed to achieve a more conclusive value for the maintenance requirements for laying hens.

The current marginal costs of the 3 AA in this study were \$1.50/kg for L-Lys HCl, \$3.50/kg for DL-Met, and \$2.10/kg for L-Thr. Current

prices for the 4 egg grades used in Brazil were \$0.0825/egg. From these values, k was calculated as 0.00113, 0.00263, and 0.001158 for the 3 AA, and the additional amount of Lys, Met+Cys, and Thr worth feeding above the mean was 251, 204, and 195 mg, respectively. The optimum economic AA intake of 3 three test AA for laying hens weighing 1.45 kg and producing 55 g egg output was calculated to be 776, 715, and 619 mg/bird per day, respectively.

A range of cost ratios (k) representing 15, 30, and 45% above and below the current value for each AA was used to calculate the optimum economic intakes of the 3 AA under test for 3 $E_{\max}$ (45, 50, and 55 g/bird per day) and 3 mean BW (1.45, 1.55, and 1.75 kg). Results are given in Table 11. Predictably, the optimum economic

AA intake decreased as the ratio of marginal cost to marginal revenue increased (Table 11).

Egg producers should be aware that the optimum economic supply of essential nutrients is not static but varies according to supply and demand and, thus, market prices. Hence the need to recalculate this optimum whenever the cost:benefit ratio changes. But the optimum economic AA intakes were not only a function of the cost ratio (k) but also of BW and $E_{\max}$. As these variables increase so does the rate of protein synthesis, and more AA are required.

Taking Lys as an example, for a hen with a 55 g $E_{\max}$ and a BW of 1.45 kg the optimum Lys intake ranged from 761 to 799 mg/bird per day as a function of k (Table 11) and for a fixed k value of 0.001, the current value in Brazil,

Table 11. Optimum economic amino acid intake (milligrams/bird per day) as influenced by potential egg output (grams/hen per day), mean BW (kilograms), and cost ratios (k)¹.

Egg output	BW	Cost ratio (k) ²						
		0.00062	0.0008	0.00096	0.00113	0.0013	0.0015	0.00163
Lysine								
		1.45	714	705	697	691	685	680
	45	1.55	717	708	701	694	689	683
		1.75	725	716	708	701	696	691
		1.45	757	747	740	733	728	723
	50	1.55	760	751	744	737	731	726
		1.75	768	758	751	744	739	734
		1.45	799	790	783	776	771	766
	55	1.55	803	794	786	780	774	769
		1.75	810	801	794	787	782	777
Methionine + cysteine		0.00145	0.0018	0.00224	0.00263	0.00302	0.0034	0.00381
		1.45	659	650	642	635	629	624
	45	1.55	664	655	647	640	635	629
		1.75	674	665	657	651	645	639
		1.45	699	690	682	675	669	664
	50	1.55	704	695	687	680	674	669
		1.75	714	705	697	690	685	679
		1.45	739	729	722	715	709	704
	55	1.55	744	734	727	720	714	709
		1.75	754	745	737	730	724	719
Threonine		0.00087	0.0011	0.00134	0.00158	0.00181	0.0021	0.00229
		1.45	570	562	556	551	547	543
	45	1.55	573	566	560	555	551	547
		1.75	581	574	568	562	558	554
		1.45	603	596	590	585	580	576
	50	1.55	607	600	594	589	584	580
		1.75	615	607	601	596	592	588
		1.45	637	630	624	619	614	610
	55	1.55	641	633	627	622	618	614
		1.75	648	641	635	630	625	621

¹[54].

² k = marginal cost of amino acid (\$/milligram) / marginal revenue for egg output (\$/gram).

the optimum intakes ranged from 691 to 787 mg/day depending on maintenance and potential egg output. This demonstrates the wide range of intakes that could be regarded as optimal depending on the prevailing conditions and strain used. The optimum intake of 780 mg Lys/day is lower than that recommended by the BTPS [17] for laying hens BW 1.5 kg and producing 55.5 g of $E_{\max}$. However, the purpose of this series of response trials was to describe the responses of laying hens to AA and not to determine their 'requirement,' which is a concept that should not be applied to populations or flocks of laying hens.

The optimum intakes of the 3 AA derived using this approach are expressed in milligrams/bird per day, but to formulate a feed it is necessary to know how much the hen is likely to consume. Unfortunately, FI does not remain constant as the AA concentration in the diet is changed, so FI needs to be predicted before the amount of each AA can be accurately supplied to the birds. If an intake of 104 g/day were to be guaranteed, and the mean BW of the flock was 1.45 kg with a mean $E_{\max}$ of 55 g, the concentrations of Lys, Met+Cys, and Thr required in the feed would be 7.46 ($k = 0.00113$), 6.88 ($k = 0.00263$), and 5.95 g/kg ($k = 0.00158$), respectively.

Depending on the ingredients available, and their prices, the marginal cost of each AA will vary, but not all AA need necessarily be limiting in the feed and hence their marginal costs may not be realistic. It is not necessary to attempt to restrict all the essential AA to their lower bound as defined using the RM approach: only those AA that are limiting in the formulation would be at the lower bound, whilst all others should be allowed to run free. In feed formulations for laying hens that are based on maize and soybean meal, Met+Cys are the first limiting AA.

CONCLUSIONS AND APPLICATIONS

1. Factorial models make it possible to estimate AA requirements for a population, considering the variation in genetic potential in the population. Mechanistic models are then needed to simulate the actual performance of these genotypes to feeds of differ-

ent nutrient content, from which decisions can be made regarding the optimum economic feeds and feeding programs to use under different circumstances.

2. The Reading model proposed for laying hens to estimate optimum AA intakes for a population takes into account the economic aspects and hence may be used to determine the optimum economic intake of AA for populations of laying hens under different genetic and economic circumstances.
3. In conclusion, a modeling approach is possibly the best way to determine the optimum economic feeding program for broilers and laying hens, and for predicting performance in the future.

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